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Excitonic Diamagnetic Shifts and Magnetic Field Dependent Linewidths in $\text{Al}_x\text{Ga}_{1-x}\text{As}$ Alloys

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ABSTRACT

We report measurements of both the diamagnetic shifts and the linewidths of excitonic transitions in $\text{Al}_x\text{Ga}_{1-x}\text{As}$ alloys as a function of Al concentration and magnetic field at 1.4 K using photoluminescence spectroscopy. The magnetic field was varied from 0 to 13 tesla and Al composition in our samples ranged from 0 to 30%. The samples were grown on GaAs substrates oriented along [001] direction using molecular beam epitaxy at 590°C. We find that for a given value of alloy composition, both the diamagnetic shift and excitonic linewidth increase as a function of magnetic field. To explain our experimental data we propose that the excitons are localized in a very specific manner. To simulate this localization, we assume that the exciton reduced mass is effectively increased and is obtained by using the alloy dependent heavy-hole mass along (001) direction treated isotropically. The calculated values of the variations of the diamagnetic shift and excitonic linewidth as a function of magnetic field obtained using this model agree very well with those reported here.

INTRODUCTION

One of the most commonly used optical characterization techniques to assess the quality of a semiconductor alloy is the low-temperature photoluminescence (PL) spectroscopy. At liquid helium temperatures, the linewidth of an excitonic transition defined as the full-width-at-half-maximum (σ) in semiconductor alloys as determined by PL spectroscopy is considerably larger than those observed in their components. This broadening has been attributed to the compositional disorder [1-8] which is inevitably present in these systems. In addition, the value of σ can be controlled by the application of an external magnetic field as was first pointed out independently by Raikh and Éfros [8], and Singh and Bajaj [2]. This is due to the fact that the application of a magnetic field shrinks the excitonic wave function and thus enhances the value of σ . This effect was first observed by Jones et al [9] in InGaP lattice matched to GaAs.

During the past twenty years several groups [10] have studied the variation of σ as a function of alloy composition in AlGaAs. In this paper we present an observation of the variations of the diamagnetic shift of the excitonic transition (δ) and σ as a function of magnetic field in AlGaAs at 1.4 K using PL spectroscopy. The Al composition x ranged from 0 to 0.30 and the magnetic field was varied from 0 to 13 tesla. We find that for a given value of alloy composition, both δ and σ increase as a function of magnetic field. The observed variations of δ and σ with magnetic field

are considerably smaller than those calculated by Lee and Bajaj[6] using a free exciton model. To explain our experimental data we propose that the excitons are localized in a very specific manner. In order to simulate this localization, we assume that the reduced mass of the exciton is effectively increased. In addition, we postulate that the conduction-band mass is unchanged, thereby requiring the use of a larger value for the valence-band mass. We find that the value of the heavy-hole mass along the [001] direction, when used to obtain the reduced mass, leads to the values of δ for all samples that agree very well with the calculated values. Furthermore, the observed variation of σ with magnetic field is in very good agreement with that calculated using this larger reduced mass.

EXPERIMENTAL

All of the AlGaAs samples reported here were grown on (001) oriented undoped GaAs substrates by molecular beam epitaxy at 590°C. A structure consisting of a smoothening 300-nm-thick epilayer of GaAs grown on top of the GaAs substrate followed by a double heterostructure of undoped $\text{Al}_{x+0.1}\text{Ga}_{1-x-0.1}\text{As}/\text{Al}_x\text{Ga}_{1-x}\text{As}$ with 50-nm-thick barriers and a 50-nm-thick $\text{Al}_x\text{Ga}_{1-x}\text{As}$ alloy was studied here. In this manner, the $\text{Al}_{x+0.10}\text{Ga}_{1-x-0.10}\text{As}$ barriers prevented carriers and excitons from diffusing to GaAs. A 10-nm-thick undoped cap-layer of GaAs was grown on top of the AlGaAs double heterostructure to prevent oxidation. The compositions were verified by comparing the lattice constants of the samples obtained from double x-ray scattering, with the well known composition dependence of the bandgap energy for these alloys [11]. The PL measurements were made at 1.4 K using the 514.5-nm line from an argon-ion laser. Laser power densities ranged from 0.1 $\mu\text{W}/\text{cm}^2$ to 100 mW/cm^2 . The PL lineshape and linewidth were found to be independent of excitation intensity for these low power densities.

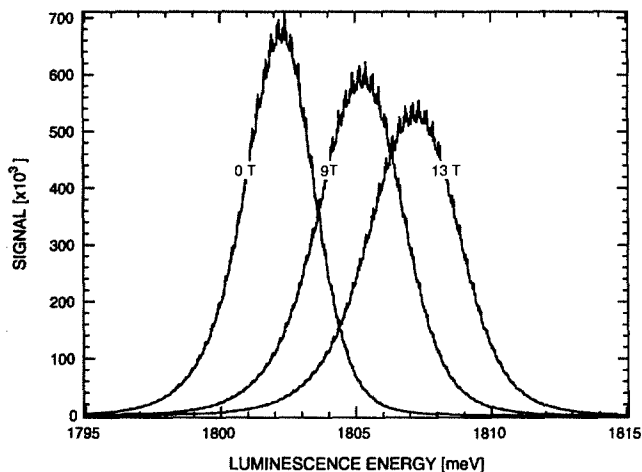


Figure 1. Photoluminescence spectrum of $\text{Al}_{0.20}\text{Ga}_{0.80}\text{As}$ at 1.4 K for different values of the magnetic field B . The leftmost spectrum is the zero-field case, the center spectrum is for $B = 9$ tesla, and the rightmost spectrum is for $B = 13$ tesla.

RESULTS AND DISCUSSION

In Fig. 1 we display typical PL spectra for $\text{Al}_{0.2}\text{Ga}_{0.8}\text{As}$ at 1.4 K for three different values of the magnetic field, namely 0, 9, and 13 tesla. The position of the zero-field excitonic transition is at 1802.3 meV. As clearly seen in Fig. 1, with increasing magnetic field, this transition broadens and shifts to higher energies. Data similar to those shown in Fig. 1 are obtained in all other samples reported here.

A number of groups have reported calculations of σ as a function of alloy composition in completely disordered semiconductor alloys both in the absence [1-6] and in the presence of magnetic field [7-8, 12]. A brief review of these calculations has been presented in Refs. 6 and 7. All these calculations are based on the premise that excitons created in different regions of the semiconductor alloy experience slightly different values of the local conduction and valence-band edges, assuming virtual crystal approximation. This leads to different values of the emission energies from the different regions of the alloy thus resulting in an inhomogeneously broadened transition.

We have calculated the variation of δ as a function of magnetic field using the formalism of Lee and Bajaj [6] using a variational wave function proposed by Fedders [13]. We have considered two cases. In the first we assume that the radiative transitions in $\text{Al}_x\text{Ga}_{1-x}\text{As}$ result from free excitons and in the second from localized excitons. To simulate the behavior of radiative transitions due to localized excitons we assume the exciton reduced mass is effectively enhanced. We further postulate that there is no change in the electron mass and only the hole mass is increased. It turns out, surprisingly, that the value of the heavy hole mass along the direction of the magnetic field, i.e., (001), when treated isotropically to obtain the exciton reduced mass yields values of the variation of δ and σ with magnetic field which agree very well with those determined experimentally as is discussed in the following.

In Figs. (2a-c) and (3a-c) we show the comparisons between the results of our measurements (squares) and those of our calculations (lines) for diamagnetic shift δ and σ , respectively, as a function of magnetic field in $\text{Al}_x\text{Ga}_{1-x}\text{As}$ alloys for $x = 0.11$, $x = 0.20$ and $x = 0.30$. Similar behavior is observed in all other samples. The values of the various physical parameters for the AlGaAs alloy system used in our calculations are obtained by linear interpolations between those of GaAs and AlAs [6]. In Figs (2a-c) we find that the variations of δ as a function of the magnetic field, reported here, agree very well with those calculated using the above mentioned localized exciton model. The calculated values using the free exciton model are considerably larger.

It is clear from Figs. (3a-c) that the observed values of σ are always larger than the calculated ones. This is due to the fact that in our calculations we consider only the broadening effect due to alloy disorder.

We have also measured the diamagnetic shift in different crystallographic directions and found no change in its value, thus suggesting that the localized excitons have spherical symmetry. The nature of the localization phenomenon is not understood at this time. Currently, experimental work is in progress to gain further insight into this phenomenon.

CONCLUSION

In summary, we have measured both the diamagnetic shifts and the linewidths of excitonic transitions in a series of $\text{Al}_x\text{Ga}_{1-x}\text{As}$ alloys as a function of Al concentration and magnetic field at 1.4 K using photoluminescence spectroscopy. The magnetic field was varied from 0 to 13 tesla

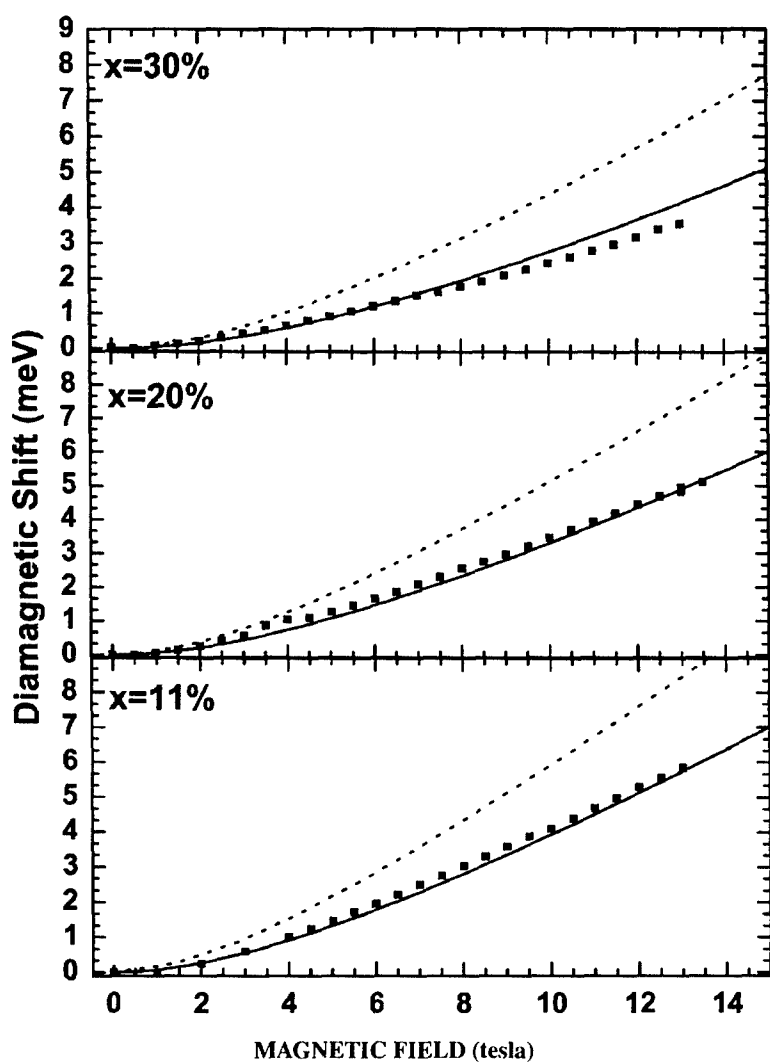


Figure 2. Variation of the diamagnetic shift of the excitonic transitions in $\text{Al}_x\text{Ga}_{1-x}\text{As}$ as a function of magnetic field for three different Al concentrations: (a) $x = 11\%$, (b) $= 20\%$, and (c) $= 30\%$. Dashed curves: calculated using the free exciton model; solid curves: calculated using the excitonic reduced mass obtained using heavy-hole mass along (001) direction. Symbols represent experimental data.

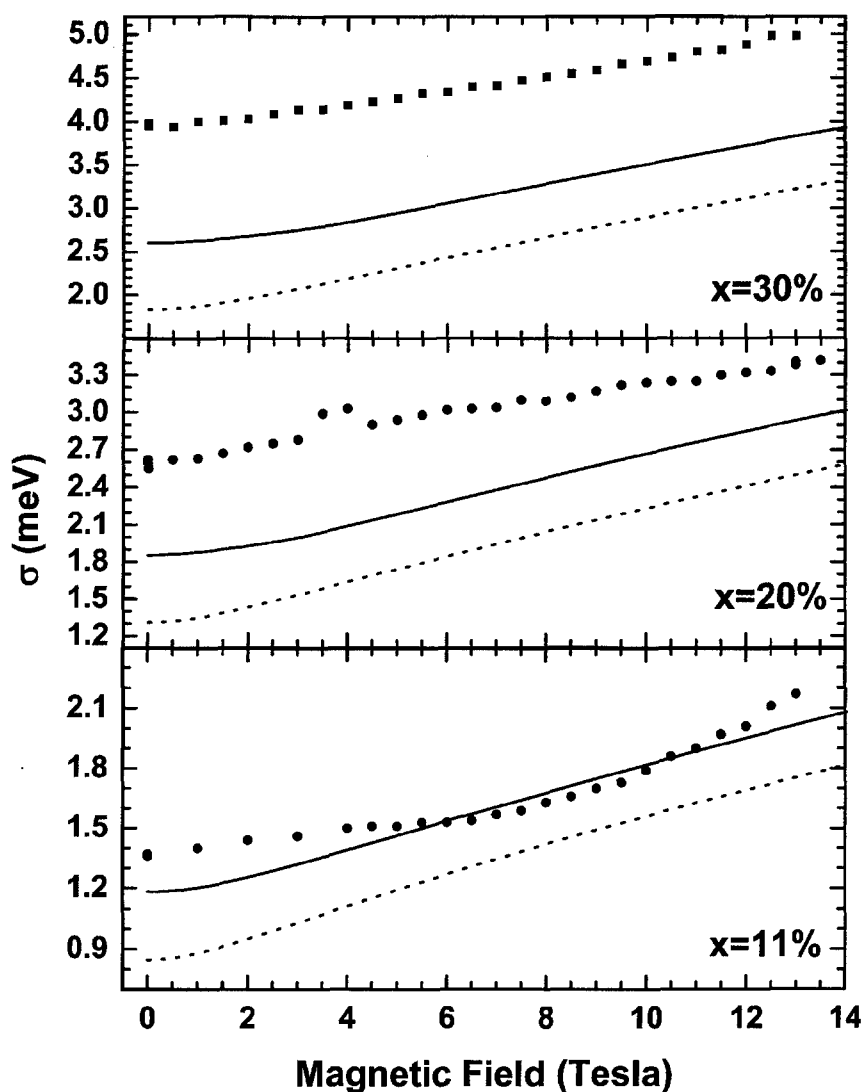


Figure 3. Variation of the excitonic linewidth (σ) in $\text{Al}_x\text{Ga}_{1-x}\text{As}$ as a function of magnetic field for three different Al concentrations: (a) $x = 11\%$, (b) $= 20\%$, and (c) $= 30\%$. Dashed curves: calculated using the free exciton model; solid curves: calculated using the excitonic reduced mass obtained using heavy-hole mass along (001) direction. Symbols represent experimental data.

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